6. Infrared thermometer calibrations

6.1 Radiation pyrometer preparation

Radiation thermometers (RT) are measured for the temperature range from 800 °C to 2700 °C. The RTs are operated according to the manufacturer's operating instructions unless special instructions are given. First, the lens, eyepiece, and filters are cleaned; then the emissivity control is set to unity. The RT is aligned so that its optical axis, when viewing the VTBB, coincides with the geometrical center of the blackbody.

6.2 Radiation pyrometer calibration

The VTBB is turned on and set to the highest temperature measured. After waiting 30 min, the PEP is used to determine the radiance temperature of the VTBB by spectrally comparing it to the WS lamp at each calibration temperature from 2700 °C to 800 °C in 100 °C steps. The measurements are repeated at 2300 °C, 1900 °C, 1500 °C, 1100 °C, and 800 °C to determine the stability of the RT. The VTBB is compared to the WS three times, and the average of the measurements is used. After the temperature of the VTBB is determined, three RT measurements of the VTBB are made, and the output current, output voltage, or indicated temperature is recorded. The spectral radiance temperatures of the VTBB used in the calibration are determined at wavelengths of 655.3 nm, 900 nm, and 1000 nm. For 100 °C temperature changes, the VTBB is measured after waiting 5 min for the VTBB to stabilize.

6.3 Radiation pyrometer data analysis

For RTs with output currents or voltages, the nominal temperature, the VTBB temperature, and the output current or voltage are reported in the test report. For RTs with temperature indicators, the nominal temperature, the VTBB temperature, the temperature indicated by the RT, and the RT correction are reported in the test report. The RT correction is equal to the VTBB temperature minus the RT indicated temperature.

6.4 Radiation pyrometer calibration uncertainty

To calibrate radiation thermometers (RT), the ratio (r_4) of the spectral radiance of the WS lamp to that of the variable-temperature blackbody (BB),

$$r_4 = \frac{L_l(T_{\mathrm{RT}})}{L_l(T_{\mathrm{WS4}})} = \frac{S_{\mathrm{RT}}}{S_{\mathrm{WS4}}} , \tag{54}$$

is first measured to determine the radiance temperature of the BB, $T(8, L_{8\mathrm{BB}})$, at each test temperature by the equation,

$$T_{\mathrm{BB}} = \frac{c_2}{n_l \cdot l \cdot \ln\left[1 + \dfrac{e_{l,\mathrm{RT}} \cdot c_{1\mathrm{L}}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS4}} \cdot r_4} \cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}\right]} . \tag{55}$$

The uncertainty in the spectral radiance of the BB can be calculated by the RSS of the products of the partial derivatives in eqs (57) through (60) with their respective uncertainties,

$$u_0(T_{\mathrm{BB}}) = \left[\left(\frac{\partial T_{\mathrm{BB}}}{\partial n_l} \cdot u(n_l)\right)^2 + \left(\frac{\partial T_{\mathrm{BB}}}{\partial l} \cdot u(l)\right)^2 + \left(\frac{\partial T_{\mathrm{BB}}}{\partial c_2} \cdot u(c_2)\right)^2 + \sum_{i=1}^{12}\left(\frac{\partial T_{\mathrm{BB}}}{\partial x_i} \cdot u(x_i)\right)^2\right]^{1/2}, \tag{56}$$

where x_i is one of the following variables: e_{RT}, c_{1L}, r_4, $C_{\mathrm{A,WS}}$, $C_{\mathrm{L,WS}}$, $C_{\mathrm{S,WS}}$, G_{WS}, $C_{\mathrm{A,BB}}$, $C_{\mathrm{L,BB}}$, $C_{\mathrm{S,BB}}$, or G_{BB}. From eq (55), the partial derivatives of n_l, l, and c_2 are

$$\frac{\partial T_{\mathrm{BB}}}{\partial n_l} = \frac{T_{\mathrm{BB}}}{n_l} \cdot \left[\frac{e_{l,\mathrm{RT}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS4}}} \cdot \frac{2 \cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_4 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}}\right)} - 1\right], \tag{57}$$

$$\frac{\partial T_{\mathrm{BB}}}{\partial l} = \frac{T_{\mathrm{BB}}}{l} \cdot \left[\frac{e_{l,\mathrm{RT}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS4}}} \cdot \frac{5 \cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_4 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}}\right)} - 1\right], \text{ and} \tag{58}$$

$$\frac{\partial T_{\mathrm{BB}}}{\partial c_2} = \frac{T_{\mathrm{BB}}}{c_2}. \tag{59}$$

The expression,

$$\left|\frac{\partial T_{\mathrm{BB}}}{\partial x}\right| = \frac{T_{\mathrm{BB}}}{x} \cdot \frac{e_{l,\mathrm{RT}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS4}}} \cdot \frac{\cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_4 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}}\right)}, \tag{60}$$

represents the partial derivatives of T_{BB} with respect to x, where x is one of the variables, e_{RT}, c_{1L},

r_4, $C_{A,WS}$, $C_{L,WS}$, $C_{S,WS}$, G_{WS}, $C_{A,BB}$, $C_{L,BB}$, $C_{S,BB}$, or G_{BB}.

Table 13 shows the typical values of the variables in eq (55). The uncertainties of eq (56) are displayed in table 14. Finally, the total expanded uncertainty shown in table 14 is

$$\frac{u(T_{\mathrm{BB}})}{T_{\mathrm{BB}}} = \left[\left(\frac{u_0(T_{\mathrm{BB}})}{T_{\mathrm{BB}}}\right)^2 + \left(\frac{u(\mathrm{DMM})}{T_{\mathrm{BB}}}\right)^2\right]^{1/2} . \tag{61}$$

The uncertainty in the RT temperature is related to the uncertainty in the variable-temperature blackbody temperature by the following relationship,

$$\frac{u(T_{\mathrm{RT}})}{T_{\mathrm{RT}}} = \left[\frac{u^2(T_{\mathrm{BB}})}{T_{\mathrm{BB}}^2} + \left(\frac{u(\mathrm{BU})}{T_{\mathrm{RT}}}\right)^2 + \left(\frac{u(\mathrm{RTR})}{T_{\mathrm{RT}}}\right)^2\right]^{1/2} . \tag{62}$$

From tables 13 and 14, the relative expanded uncertainty in the T_{RT} is 3.05 K/2579.07 K, or 0.12 %. For other RT temperatures, table 2 can be used to approximate the uncertainties.

Table 13. Typical values of RT variables and parameters

Variable	Symbol	Value
Refractive index	n_l	1.00028
Wavelength	l	655.3 nm
Second radiation constant	c_2	14387.69 µm·K
Emissivity of BB	e_{BB}	0.99
First radiation constant	c_{1L}	1.191 x 10^8 W·µm^4·m^{-2}
WS spectral radiance	L_{WS}	569.9 W·m^{-2}·µm^{-1}·sr^{-1}
Ratio of BB signal to WS signal	r_4	3.445
WS amplifier calibration correction	$C_{\mathrm{A,WS}}$	0.09986
WS linearity correction	$C_{\mathrm{L,WS}}$	1
WS size of source correction	$C_{\mathrm{S,WS}}$	1
WS amplifier gain	G_{WS}	1 x 10^9 V·A^{-1}
BB amplifier calibration correction	$C_{\mathrm{A,BB}}$	9.978
BB linearity correction	$C_{\mathrm{L,BB}}$	0.9997
BB size of source correction	$C_{\mathrm{S,BB}}$	0.9987
BB amplifier gain	G_{BB}	1 x 10^7 V·A^{-1}
BB temperature	T_{BB}	2579.07 K

Table 14. Uncertainty budget for the RT temperature calibration

Uncertainty component	Symbol	Expanded Uncertainty (k = 2) Type A	Type B
Refractive index	$u(n_l)$		0.00002
Wavelength	$u(l)$		0.2 nm
Second radiation constant	$u(c_2)$		0.24 µm·K
Emissivity of BB	$u(e_{BB})$		0.0002
First radiation constant	$u(c_{1L})$		440 W·µm^4·m^{-2}
WS spectral radiance	$u(L_{WS})$		2.998 W·m^{-2}·µm^{-1}·sr^{-1}
Ratio of BB signal to WS signal	$u(r_4)$	0.00579	
WS amplifier calibration correction	$u(C_{A,WS})$	0.00001	
WS linearity correction	$u(C_{L,WS})$	0.001	
WS size of source correction	$u(C_{S,WS})$	0.0002	
WS amplifier gain	$u(G_{WS})$		0 V·A^{-1}
BB amplifier calibration correction	$u(C_{A,BB})$	0.001	
BB linearity correction	$u(C_{L,BB})$	0.001	
BB size of source correction	$u(C_{S,BB})$	0.0002	
BB amplifier gain	$u(G_{BB})$		0 V·A^{-1}
Digital voltmeter	u(DMM)		0 K
BB temperature	$u(T_{BB})$		2.29 K
Blackbody uniformity	u(BU)	0.20 K	
RT reading	u(RTR)	2.00 K	
RT temperature calibration	$u(T_{RT})$	**3.05 K**	